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Accuracy and Sensitivity Analyses of SAIL Model-Predicted Reflectance of Maize*

D. J. Major,[†] G. B. Schaalje,[†] C. Wiegand,[‡] and B. L. Blad[§]

[†]Agriculture Canada, Lethbridge, Alberta, Canada, [‡]USDA-ARS, Weslaco, Texas, and [§]University of Nebraska, Lincoln

Bidirectional reflectance of six maize genotypes was measured on 16 dates in 1984 at the Nebraska Sandhills Laboratory using a modular multiband radiometer. On 10 of the dates, measurements were repeated during the day to obtain a range of solar zenith angles. Plants were sampled approximately weekly to determine leaf area index (LAI) and smoothed to provide LAI values for each of the 560 reflectance measurements. Reflectance in the red and near-infrared (NIR) was predicted by three versions of the SAIL model, a one-dimensional version, a two-dimensional version that took rows into account, and a modified two-dimensional version that accounted for shading caused by rows and crop height, and then evaluated using an accuracy analysis that considered bias, regression, and random errors. The results indicated that the 1-D SAIL model underestimated red and overestimated NIR reflectance at partial canopies because it did not account for exposed bare soil. The 2-D version, which accounted for ground cover, generally overcame this problem. The 2-D′ version, which accounted for shading of soil and canopy due to increasing canopy height, did not improve the results of the 2-D version enough to warrant the increased complexity. Sensitivity analyses, in which the main inputs required to fit the data were varied, revealed that the same leaf angle distribution and the same single leaf reflectance and transmittance values could be used for the whole season. Diurnal, multitemporal reflectance combined with the SAIL model adequately described the radiative transfer properties of the maize crop canopies studied.

INTRODUCTION

The contrast in the red and near-infrared wavebands between the soil background and live vegetation contains most of the information in spectral observations of crop canopies. Combining the reflectance in these two regions into a vegetation index provides information about the leaf area index (LAI) (Asrar et al., 1984) and absorbed photosynthetically active radiation (APAR) (Daughtry et al., 1983). However, other factors, including reflectance from the soil background (Huete, 1988; Major et al., 1991a), the average angular distribution of the foliar elements or the leaf angle distribution (LAD) (Bunnik, 1978), and the single leaf reflectance and transmittance (Baret et al., 1989a), may interfere with determination of LAI and APAR from spectral observations. Additionally, the atmosphere, solar zenith angle, and the instrument view angle affect spectral observations. The variables are so numerous and interactive that mathematical models of the crop's spectral re-

* Journal Series No. 9764 Agricultural Research Division, University of Nebraska.

Address correspondence to D. J. Major, Agriculture Canada, Research Station, P. O. Box 3000, Main, Lethbridge, Alberta T1J 4B1, Canada.

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sponse are needed to describe the interactions as LAI and chlorophyll content of the canopy vary.

The most numerous and useful models to describe light interactions in crop canopies belong to the group of turbid media radiative transfer models reviewed by Goel (1987) based on extensions of the original Kubelka–Munk equations cited by Suits (1972). Verhoef (1984) modified the Suits model to produce the SAIL (Scattering by Arbitrarily Inclined Leaves) model.

A new and increasingly practical approach is to invert canopy reflectance models to estimate LAD, LAI, leaf reflectance and transmittance, and soil reflectance. The SAIL model has been successfully inverted (Goel and Thompson, 1984) using measurements of the same canopy at different view and solar zenith angles. The SAIL model, however, is one-dimensional (1-D) and does not account for row effects. A modification such as TRIM (three-dimensional radiation interaction model) (Goel and Grier, 1988) makes the SAIL model capable of accounting for row effects. Additional dimensions make the model more complex but more accurate, if the phenomena described are correctly represented in the simulation. Our objectives in this study were to estimate LAI by inverting the SAIL model, to compare the agreement with reflectance observations among versions of SAIL of differing dimensionality, and to perform accuracy and sensitivity analyses on selected parameters of the SAIL model.

MATERIALS AND METHODS

Field Experiments and Biophysical Measurements

Spectral reflectance and physiological measurements of five maize hybrids grown at Tryon, Nebraska in 1984 were used to test the capability of the SAIL model to simulate canopy reflectance. The experimental treatments included the hybrids Pioneer 3901 at full (7.5 plants m^{-2}) and half (4.6 plants m^{-2}) population densities, B73×Mo17, and three Standard Oil hybrids (S3, S6, and S12) under fully and partially irrigated conditions. The experiment has been described in detail by Wiegand et al. (1990).

The Tryon site is located at latitude 41°37'N and longitude 100°50'W and the soil is a Valentine fine sand (Typic Ustipsaments). The experiment was seeded in a four replicate, split-plot design with irrigation treatments as the main plot and hybrids as subplots. All plots received 176 kg N ha^{-1} prior to seeding. Emergence occurred on 24 May, silking between 31 July and 7 August and black layer maturity between 29 September and 9 October. Plant samples were taken weekly; 5 and 20 June, 4, 11, 19, and 26 July, 2, 8, 22, and 30 August, and 12 September. Green leaf and whole-plant mass and green leaf area index were determined on each of the sampling dates.

Canopy reflectance was measured with a Barnes Modular Multiband 12-1000 Radiometer (Robinson and Biehl, 1979) suspended over the crop canopy 5 m above the ground surface. The radiometer was truck-mounted on a boom, and a nadir view angle was used. The field of view was 15°. Data were acquired on 16 dates, and on 10 of those dates diurnal measurements provided a range of solar zenith angles. The measurement dates were: 6, 19, 27, 28, and 29 June, 6, 12, and 24 July, 4, 5, 7, 8, 9, 11, 23, and 30 August, and 13 September. At the start and end of measurements, and at intervals of no more than 20 min, reflectance from a pressed $BaSO_4$ panel was measured. Reflectance values were converted to bidirectional reflectance factors (BDRF) using the method described by Robinson and Biehl (1979). Leaf area index values on the dates of the reflectance measurements were obtained by graphing the periodic LAI measurements versus time and interpolating the LAI value from the smoothed curves.

SAIL Model Parameters

The SAIL model requires information about four canopy parameters: i) LAI, ii) leaf angle distribution (LAD, θ_L), iii) single leaf reflectance (ρ) and transmittance (τ), and iv) soil reflectance R_s. The external requirements are: i) solar zenith (θ_s) and azimuth (ψ_s) angles, ii) instrument view (θ_0) and azimuth (ψ_0) angles, and (iii) proportions of direct and diffuse sunlight. In this study, we had measurements of LAI, soil reflectance, solar zenith and azimuth angles, and the instrument view angle was 0°. Since measurements were taken only on clear days we assumed that the diffuse contribution of incoming radiation was 15% (Spitters et al., 1986).

The unknown quantitites were LAD, ρ, and τ. Until recently, these quantities were difficult to investigate because of tedious measurements in the case of LAD and because of the requirement for a high resolution spectrometer with integrating sphere for ρ and τ. But there is evidence that LAD does not change much throughout the season (Rigal and Teres, 1988). To our knowledge, there have been no studies of how ρ and τ change during the season, although the "red shift" shows that the dramatic increase in ρ and τ between the red and near-infrared is altered by factors that affect chlorophyll content (Lichtenthaler and Buschmann, 1987).

Goel and Thompson (1984) demonstrated that the SAIL model can be inverted if enough canopy reflectance measurements are taken to fully represent all of the illumination parameters and views. Goel and Strebel (1984) showed that LAD can be represented by a beta distribution, characterized by two parameters μ and ν. They inverted the SAIL model using a data set in which the angles θ_s and θ_0 and canopy reflectance were measured 12 times during 1 day. Major et al. (1991b) inverted the SAIL model using data from a maize experiment and found that seasonal differences in LAD, ρ, and τ had an insignificant effect on the results of the inversion. We assumed that LAD could be represented by a single parameter (θ_L), and that θ_L, ρ, and τ were seasonally stable. In this study, the value of θ_L was chosen as that which resulted in the best fit between measured LAI and SAIL-derived estimates of LAI. Values for the spectral parameters, ρ and τ, were obtained similarly by comparing canopy reflectance measurements with SAIL-derived canopy reflectance at full canopy and assuming that ρ and τ are the dominant canopy parameters at that point in the season.

The SAIL model is one-dimensional so may not respond appropriately for a row crop such as maize without including parameters that take row effects and perhaps height and shading into account. Goel and Grier (1988) used parameters for row spacing and for spacing of plants within the row to account for row effects on the amount of ground area covered by the canopy and the amount that was exposed. This correction to the SAIL model makes it two-dimensional.

The two-dimensional SAIL model can be further modified by incorporating plant height so that shading can be considered. The simple model for calculating the amount of sunlit canopy and soil, and shaded canopy and soil described by Strahler and Jupp (1990) was used here for that purpose.

SAIL Model Inversion

In this study the SAIL model was inverted for each of the 560 observations as follows. The SAIL model was run with values of LAI ranging from 0 to 5 to estimate a set of (MMR3) and (MMR4) reflectances. These were used to produce the transformed soil adjusted vegetation index (TSAVI) (Baret et al., 1989b) using:

$$\mathrm{TSAVI} = \frac{b_1\ \mathrm{MMR4} - b_1^2\ \mathrm{MMR3} - b_0 b_1}{\mathrm{MMR3} + b_1\ \mathrm{MMR4} - b_0 b_1}, \quad (1)$$

where b_0 (1.93) and b_1 (1.26) are the intercept and slope of the bare soil line (Wiegand et al., 1990). An extinction coefficient (k) relates TSAVI to LAI by the equation (Baret et al., 1989b)

$$\mathrm{TSAVI}_c = \mathrm{TSAVI}_\infty + (\mathrm{TSAVI}_s - \mathrm{TSAVI}_\infty)e^{-k\cdot \mathrm{LAI}}, \quad (2)$$

where the subscripts c, ∞, and s refer to the crop, infinite, and soil TSAVI values, respectively, and k is the extinction coefficient. Since TSAVI_s approaches zero and TSAVI_∞ approaches 1, Eq. (2) reduces approximately to

$$\mathrm{LAI} = -1/k[\ln(1 - \mathrm{TSAVI}_C)]. \quad (3)$$

Equation (3) was fitted by linear regression to the SAIL-generated TSAVI data and the derived value of k for every combination of day number, hybrid group, irrigation treatment, and θ_s, used to generate a value for LAI.

RESULTS AND DISCUSSION

Implementing the SAIL Model

In tuning the model, various schemes were used to determine if a separate value of ρ, τ, and θ_L for each observation would produce better overall agreement between SAIL-generated and observed reflectance. An analysis run with the best estimate of ρ, τ, and θ_L for each hybrid–water–density–time combination was no better than when single parameter estimates were used for all hybrid–water–density combinations. Therefore, single values were used. This result also suggested no large direct effect of hybrids, water regimes, or density so that these factors were ignored in further analyses.

There did appear to be a seasonal trend toward a decreasing ρ and increasing τ for MMR4. This is reasonable since an accumulation of dust and pollen, tassels and leaf senescence would reduce ρ in the NIR. The opposite effect would be expected in the red region. As mentioned, any such trends were not pronounced, and there was no benefit to including them in the model.

Estimation of Leaf Angle Distribution

The initial value of θ_L used was 46° as suggested by Rigal and Teres (1988), the value also used by Major et al. (1991b) for maize. LAD values from 30° to 75° were used in a sensitivity analysis, but there was no appreciable improvement over the 46° value. After varying all of the canopy parameters the best fit was obtained with 42°.

Estimation of ρ and τ

At maximum LAI, which averaged about 4, the maximum canopy reflectance should be close to infinite canopy reflectance R_∞, which is directly related to ρ and τ. Using the SAIL model, for Bands 3 (630–690 nm) and 4 (760–900 nm), the best-fitting values of ρ were found to be 0.03 and 0.42, respectively, and for τ, 0.03 and 0.48. By comparison, Rigal and Teres (1988) found values of 0.09 and 0.40 for ρ and 0.10 and 0.52 for τ. The equation presented by Bunnik (1978) describes R_∞ for a planophile canopy in terms of ρ and τ,

$$R_\infty = \{1 - \tau - [(1-\tau)^2 - \rho^2]^{1/2}\} / \rho. \tag{4}$$

Substituting our values of ρ and τ into Eq. (4) results in R_∞ estimates of 0.02 and 0.51. In a few instances, observed canopy reflectance reached 0.05 and 0.5 for Bands 3 and 4, respectively, so that one might assume that the canopy seldom reached R_∞ for Bands 3 and 4.

Errors in Measured Values

There are several sources of error in predictions of reflectance by the SAIL model. Measurement errors in θ_s and ψ_s would be small. Other errors would be associated with θ_L, ρ, and τ because these were held constant for hybrids and water treatments both within and among dates of measurements. There should be spatial and temporal variability in all of these variables and perhaps also some temporal changes, but the data were not available. The main measurement error is probably contained in LAI. The error associated with sampled LAI measurements is due to resource limitations that restrict sample size and to spatial variation in the plot since the reflectance and LAI estimates come from different sites within the field plots. Daughtry and Hollinger (1984) found that the natural variability of leaf area per corn plant was about 10%. The standard error of the mean in this study was also about 10%.

Measurement error also occurs in the reflectance measurements. This can be due to reference panel error, departure from lambertian characteristics as a function of solar angle, and other factors. Also, spatial and temporal variability in the crop directly result in variability in the SAIL model predictions.

The fit of SAIL model-derived reflectance estimates to measured reflectance will be affected by all of these errors and sources of variability. An error in the input LAI affects the predicted reflectance, and the error in the measured reflectance compounds the discrepancy. These errors can be described mathematically but they are difficult to estimate in practice. The temporal trajectories of LAI and reflectance in the red and NIR show large variability (Fig. 1a), but this variability is greatly reduced when reflectance is plotted against LAI (Fig. 1b). The reason for this is that most of the variability during the season was the result of hybrids, irrigation, and density. Plotting reflectance against LAI adjusts for the genotypic and management effects. The standard errors of the estimate for red and near-infrared reflectance were 3.9% and 5.2%, respectively (Figs. 1c,d). Given that LAI was the primary input into the SAIL model, comparable error estimates of SAIL-generated reflectance suggest a good fit, as discussed in the section on accuracy analysis.

One-Dimensional SAIL Results

SAIL model reflectance reached saturation much quicker than measured reflectance in both MMR3 and MMR4. This is apparent in Figures 2a and 2b, where a curvilinear relationship develops be-

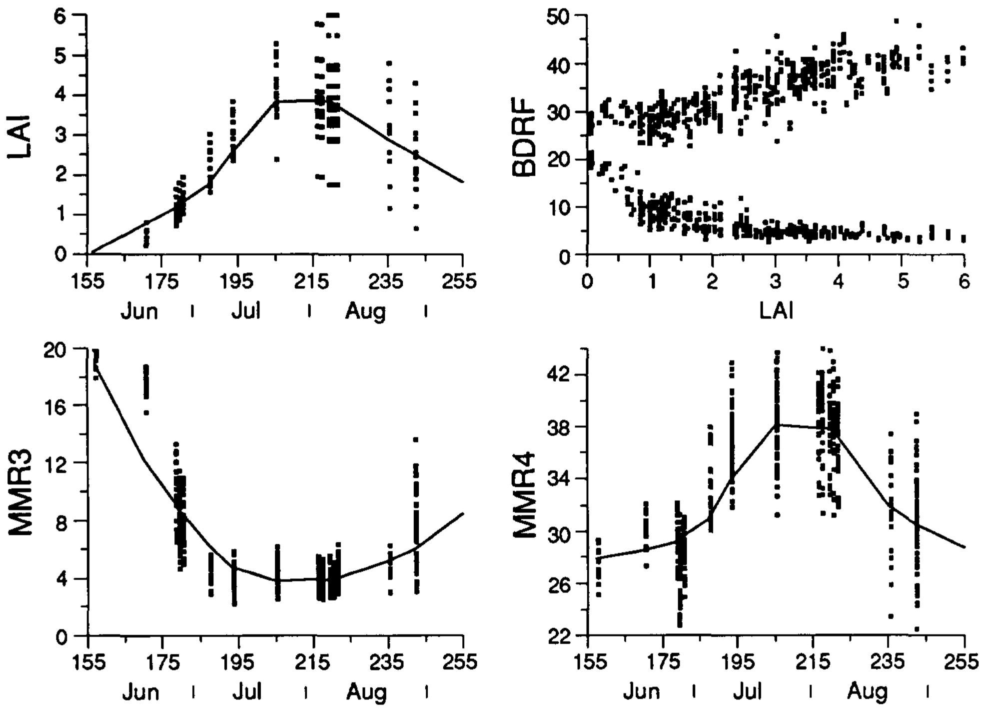


Figure 1. Seasonal and diurnal responses of LAI, red (MMR3), and near-infrared (MMR4) bidirectional reflectance factor (BDRF) versus date and MMR3 and MMR4 BDRF versus LAI for six maize hybrids grown at two irrigation levels at Tryon, Nebraska in 1984.

tween SAIL-derived reflectance and measured reflectance. The values furthest from the origin for MMR3 (Fig. 2a) and those nearest the origin for MMR4 (Fig. 2b) represent bare soil.

The rapid saturation of the SAIL reflectance in the visible waveband is obvious from Figure 2a, in which there are relatively few points between the bare soil at about 20% reflectance and the saturated reflectance at about 3%. The points that represent the developing canopy clearly fall below the 1:1 line.

The MMR4 band saturates less rapidly, and consequently there is a more uniform distribution of points across the range of reflectances. But, again, the curvilinearity indicates that the SAIL model saturates too quickly. The reason for the disagreement between the SAIL-derived and measured reflectances must be that bare soil was visible through the canopy, resulting in higher MMR3 measured reflectance and lower MMR4 reflectance.

The one-dimensional SAIL model (designated 1-D) is clearly inadequate to represent the maize crop sown in relatively wide rows. The closeness of full canopy and bare soil reflectances for the SAIL-derived estimates to the 1:1 line is encouraging. It appeared that correcting for the relative proportions of bare and vegetation-covered soil might correct the curvilinearity observed.

Two-Dimensional SAIL Results

The correction to make the SAIL model two-dimensional (designated 2-D) was essentially an estimation of fractional ground cover. The ground cover, GC, was estimated as the area of an ellipse,

$$GC = \pi J D, \tag{5}$$

where J and D (0.6) are the half fractions of the two axes of an ellipsoid (Goel and Grier, 1988). When only one of the parameters is greater than 0.5, a row canopy is simulated. In our study, we found by experimentation that a reasonable estimate in J as a function of LAI was as follows:

$$J = 0.075\ \mathrm{LAI} + 0.125. \tag{6}$$

Thus J varied from 0.125 at LAI = 0 to 0.5 at LAI = 5. The maximum value possible for ground cover occurs when J has a value of 0.53, which corresponds to a LAI of 5.4.

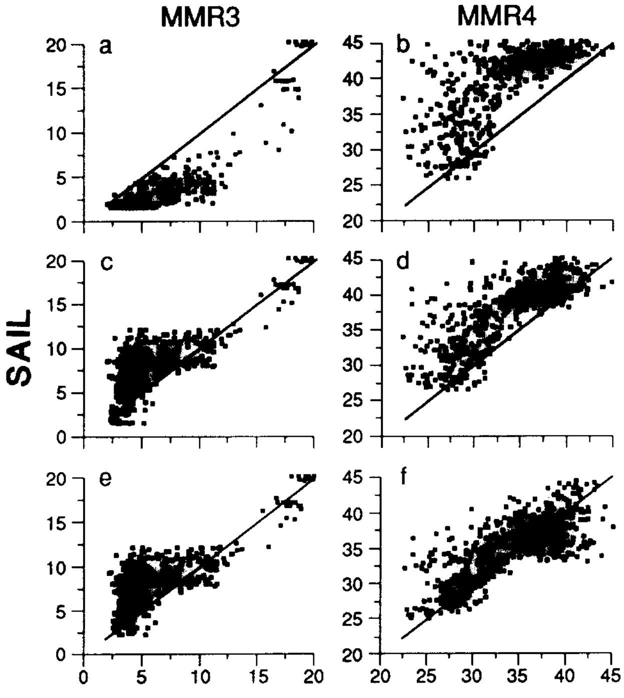


Figure 2. SAIL model generated red (MMR3) and near-infrared (MMR4) reflectance for a one-dimensional SAIL model (a and b), a two-dimensional version which accounts for ground cover (c and d), and a modified two-dimensional version accounting for shading as well as ground cover (e and f) for 560 maize observations from six hybrids, two irrigations, and 16 observation dates at Tryon, Nebraska in 1984.

SAIL-derived canopy reflectance (R_c) is defined as

$$R_c = \mathrm{GC}\ R_{\mathrm{SAIL}} + (1 - \mathrm{GC})R_s, \tag{7}$$

where R_{SAIL} is SAIL-derived reflectance for the portion of the ground covered by vegetation and R_s is bare soil reflectance. Ground cover is obtained from Eq. (5), R_{SAIL} from the 1-D model and R_s is taken from the bare soil reflectances that define the soil line.

The two-dimensional representation of the SAIL model significantly improved the fit of the SAIL-derived versus measured reflectance, eliminating much of the curvilinearity observed for the one-dimensional representation (Figs. 2c and d).

The relationship between SAIL model-derived and measured MMR3 reflectance shows that the majority of data points lie above the 1:1 line (Fig. 2c). For observed MMR3 R_c values between 3% and 5%, there was a distribution of SAIL-derived R_c values from 3% to 12%.

In the relationship between SAIL model-derived and measured MMR4 reflectance, the data points are more uniformly distributed along the 1:1 line (Fig. 2d). However, the residual sum of squares is a larger proportion of the total sum of squares because of generally large deviations from the 1:1 line.

Modified Two-Dimensional SAIL Results

The approach used to modify the two-dimensional model (designated 2-D′) was that described by Strahler and Jupp (1990) for determining amount of shaded and sunlit canopy and soil. The ground cover was again expressed in Eq. (5) and the portion of the canopy that was sunlit, K_C, was determined by

$$K_C = 0.5(1 + \cos \psi)\ \mathrm{GC}, \tag{8}$$

where ψ is the phase angle between θ_s and the θ_0 (which was always zero in this study) or between the relative azimuth angle between ψ_s (180° at solar noon) and the row azimuth angle (180°). The portion of the canopy that is shaded, K_T, is determined from

$$K_T = 0.5(1 - \cos \psi)\ \mathrm{GC}. \tag{9}$$

The fractional interrow distance that was shaded (w) was the product of canopy height (H_c) and tan ψ divided by the row width (0.75 m). Thus the total proportion of shaded soil, K_z, was determined from

$$K_z = \frac{H_c \tan \psi}{0.75}(1 - \mathrm{GC}) = w(1 - \mathrm{GC}), \tag{10}$$

and sunlit soil, K_G, from

$$K_G = (1 - w)(1 - \mathrm{GC}). \tag{11}$$

The value of w was not allowed to exceed unity so that overlapping shade was ignored. The incoming light energy in the SAIL model was handled by assuming that shaded portions of the scene received only diffuse radiation (skylight) set at 15%.

The main difference between the 2-D and 2-D′ versions was in the proportion of sunlit soil since, in the two-dimensional model, the soil not covered by the canopy was considered to be sunlit. The proportion of the shaded canopy was small. The proportion of shaded soil was also small except in a few cases such as in the early part of the season and when θ_s was high. The modified two-dimensional model improved the reflectance

Table 1. **Accuracy Analysis of Three Versions of SAIL Model-Predicted Red and NIR Reflectance of Six Maize Genotypes in Two Irrigation Treatments Measured on Six Dates at Tryon, Nebraska ($n = 560$)**

	Red Reflectance			*NIR Reflectance*		
Parameter[a]	*1-D*	*2-D*	*2-D′*	*1-D*	*2-D*	*2-D′*
Mean actual (A)	6.07	6.07	6.07	33.6	33.6	33.6
Mean predicted (P)	3.12	7.58	7.94	39.7	37.3	34.5
Mean difference ($P_i - A_i$)	−2.95	1.51	1.87	6.10	3.76	0.96
S_A	3.88	3.88	3.88	5.18	5.18	5.18
S_P	3.71	3.67	3.50	6.16	5.28	4.36
MSE $[(P_i - A_i)^2/n]$	11.7	7.36	8.62	56.1	25.6	13.2
$t_{0.05}$	−40.2	15.9	19.5	33.3	26.2	6.45
Intercept	3.14	−0.52	−1.12	9.54	4.60	3.09
Slope	0.94	0.87	0.91	0.61	0.78	0.88
Correlation coefficient (r)	0.90	0.82	0.82	0.72	0.79	0.74
U^m	0.75	0.32	0.42	0.66	0.54	0.06
U^r	0.00	0.00	0.01	0.11	0.06	0.02
U^e	0.25	0.68	0.57	0.23	0.40	0.92

[a] Standard deviation $S_A = [\sum (A_i - a)^2/(n-1)]^{1/2}$, mean square error MSE $= \sum(P_i - A_i)^2/n$, bias error $U^m = (P - A)^2/[\sum(P_i - A_i)^2/n]$, S_P = Standard deviation, predicted, regression error $U^r = (S_P - r\,S_A)^2/[\sum(P_i - A_i)^2/n]$, and random error $U^e = (1 - r^2)S_A{}^2/[\sum(P_i - A_i)^2/n]$.

estimate for NIR but not for red reflectance (Figs. 2e and f).

Accuracy Analyses of the SAIL Simulations

We used a method described by Allen and Raktoe (1981) to divide the error in prediction into three components, error due to bias, error due to regression, and error due to random effects. Bias is estimated as the ratio of the squared difference of predicted and measured, divided by the sum of the squared differences. Regression error is, in effect, the departure of the slope of actual value versus predicted value from unity and the random error is the variability about the regression.

The accuracy analyses for the three versions of the SAIL model are presented in Table 1. The one-dimensional (1-D) version of the SAIL model had a better r-value than the two- and modified two-dimensional versions, but 75% of the error was due to bias for MMR3. The error due to regression was negligible for all three versions. The 2-D version had a lower slope than the 1-D but the mean square error was also lower. Nevertheless, the proportion of error that was random was greatest for the 2-D version. It is difficult to determine which of the 2-D and 2-D′ versions for MMR3 reflectance is most accurate.

The accuracy analysis clearly favored the 2-D′ version for the MMR4 reflectance because most of the error, 92%, was random, and the data lay closest to the 1:1 line (Fig. 2f). The average difference in predicted and observed reflectance was about 1% for the 2-D′ version compared with more than 6% for the 1-D and 4% for the 2-D version. This finding suggests that the shading that occurs in crop canopies may have a significant impact on the reflectance in the near infrared. The 2-D and 2-D′ versions are less capable of detecting the canopy effects in the red region, where green vegetation absorbs very strongly.

The error because of regression was small in all cases, although it represented 11% of the error for the 1-D version for NIR. This occurred

Table 2. Accuracy Analysis of Three Versions of SAIL Model-Predicted LAI for Six Maize Genotypes in Two Irrigation Treatments Measured on Six Dates at Tryon, Nebraska ($n = 650$)

	LAI		
Parameter[a]	*1-D*	*2-D*	*2-D′*
Mean actual (A)	2.66	2.66	2.66
Mean predicted (P)	1.66	2.90	3.63
Mean difference ($P_i - A_i$)	−1.00	0.24	0.92
S_A	1.42	1.42	1.42
S_P	0.74	1.31	1.72
MSE $[(P_i - A_i)A^2/n]$	1.74	0.63	1.74
Intercept	−0.09	0.01	0.10
Slope	1.66	0.91	0.70
Correlation coefficient (r)	0.86	0.85	0.86
U^m	0.57	0.09	0.55
U^r	0.13	0.02	0.14
U^e	0.30	0.89	0.31

[a] See footnote to Table 1.

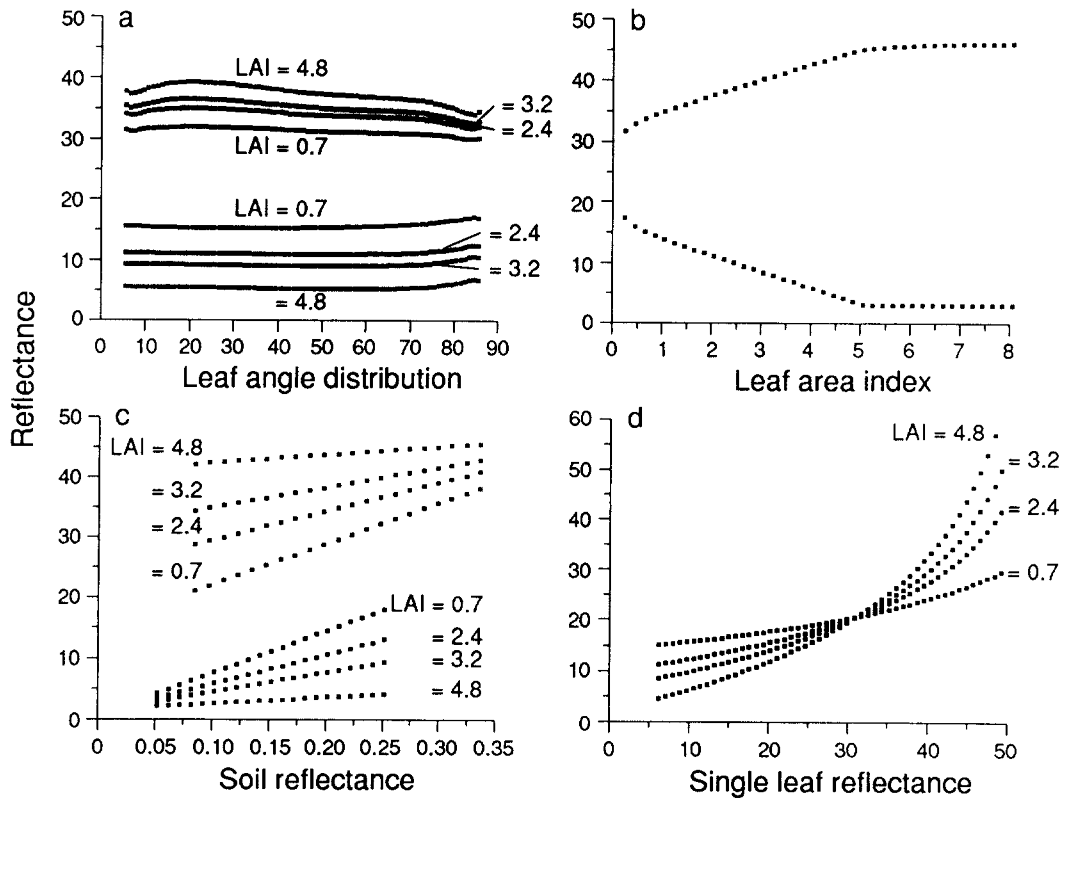
because the 1-D version does not take into account the non-random distribution of the canopy, that is, the rows. The random error is that which cannot be accounted for by the departure of the slope of actual versus predicted from the 1:1 line or of the intercept from the origin. With progressive complexity from the 1-D to the 2-D′ version of the SAIL model, the proportion of error due to random effects, U^e, increased from 23% to 92% for NIR reflectance. The results suggest that the 2-D′ version of the SAIL model as best for the NIR while the 2-D vesion was best for the red band since the random error was maximized for these results.

The results of the accuracy analyses for LAI prediction (Table 2) showed that the 1-D SAIL model underestimated and the 2-D′ SAIL model overestimated the LAI by similar amounts. Neither version could be considered completely satisfactory, due to the relatively large bias error. The 2-D version was clearly the best method for LAI inversion with intercept near zero, slope of 0.91, and almost 89% random error. Based on the consideration of the variability that exists in LAI, we concluded that, with a few exceptions, the SAIL-derived estimates of LAI were reasonable since the derivation of the SAIL-generated LAI involved only spectral reflectance considerations.

Sensitivity Analyses

Sensitivity analyses were conducted by varying one variable while holding the others constant in the 2-D′ version of the SAIL model. These included running the model with θ_L set at 42° and LAI at 0.7, 2.4, 3.2, and 4.8, the median values of the quartiles of the original data. The values of θ_s and ψ_s were 38° and 160°, respectively, the median values for the observed measurements. The values for ρ and τ were both 0.03 for red and 0.42 and 0.48 for NIR. The soil reflectance ρ_s was 0.20 for red and 0.27 for NIR. The various effects were studied by varying θ_L, from 5° to 85°; soil reflectance varied from 5 to 25 for red and 10 to

Figure 3. Sensitivity analysis showing SAIL model reflectance output for a) a range of leaf angle distributions for four LAI, b) the red and NIR reflectance for a range of LAI, c) red (lower) and NIR (upper) reflectance at four LAI for a range of soil brightness, and d) reflectance for four LAI at a range of single leaf reflectances.



35 for NIR, and ρ changed from 0.01 to 0.50. When ρ was varied, τ was set at $1.25\rho - 0.06$.

Reflectance values varied only slightly with θ_L (Fig. 3a). For changes in all other parameters the effects on reflectance were larger: decreasing red and increasing NIR reflectance with increasing LAI (Fig. 3b), increasing reflectance with increased soil reflectance (Fig. 3c), and increasing reflectance with increasing ρ and τ (Fig. 3d). One aspect that is readily apparent is that the NIR values of ρ and τ were not as high as is usually reported in the literature. Thus the effects of LAI on NIR reflectance were not as great as might be expected (Fig. 3b) and with ρ at 0.42 the differences due to LAI were minimal (Fig. 3d). If ρ had been closer to 0.50, the response to θ_L would have been greater with reflectance increasing to about 0.57 and then decreasing. The lower ρ and τ are, the less responsive R_c is to θ_L.

The response obtained for R_c versus LAI (Fig. 3b) was consistent with that obtained for the actual data in which MMR4 (Fig. 1b) increased gradually from approximately 28% at the start of the season to about 40% at LAI 5. Similarly the SAIL-generated MMR3 reflectance was similar to that of the measured MMR3 with respect to LAI.

CONCLUSIONS

This study demonstrated that the SAIL model is satisfactory for simulating canopy reflectance when it is modified to accommodate systematic canopy differences such as those caused by row effects. In this study, it was demonstrated that the model can be inverted using seasonal data and constant values of single leaf reflectance and transmittance and leaf angle distribution for the entire growing season. Errors due to inadequacies of the model and of sampling the canopy are difficult to separate. A comprehensive evaluation of the SAIL model requires seasonal trajectories of θ_L, ρ_s, ρ, and τ as well as LAI.

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